Chapter 6
Emission Models for Freeway Traffic Systems

6.1 Features and Applications

Transportation and its impact on the society and the environment are themes that have been and are being debated in any scientific, professional, politic and social contexts. Transportation yields substantial socio-economic benefits for the society, but at the same time it brings negative effects on the environment. On the one hand, transportation activities support increasing mobility demands for passengers and freight and, on the other hand, they are associated with growing levels of environmental externalities.

Among the different modes of transport, road transportation presents several advantages, since it is cost effective, fast for short-term operations, flexible (services, routes and timings can be adjusted and changed without incurring in too high costs), and typically comfortable for passengers. However, one of the main negative effects due to the predominance of the road system compared with other modes of transport is the environmental impact, which is mainly linked to the introduction of chemical pollutants, heat or greenhouse gases in the environment. *Air pollution* from automotive sources is one of the major causes of air pollution in the environment and this is even more serious for urban areas located near major roadways (see Fig. 6.1). The European Union is not insensitive to these issues, and therefore, in the past decades, severe legislations on pollutants produced by single vehicles and on their concentrations in the environmental system have been introduced. Most of the other countries all over the world have defined specific rules and legislations to deal with pollution issues as well.

The environmental issues must then be considered also in the definition of freeway traffic control schemes, which are the main topic of the present book. Besides taking care of traffic congestion phenomena, which have been central in the definition of any traffic control scheme in the last decades, it is more and more important to also tackle the environmental impact of road arterials and to explicitly consider the reduction of air pollution among the different requisites of the traffic control schemes.

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Fig. 6.1 Van Brienenoord bridge on the A16 freeway, the Netherlands (courtesy of Rijkswaterstaat, Photo: Essencia Communication/Rob de Voogd)

In view of this, it is essential to design models allowing to estimate the environmental damage produced by traffic streams or to predict the impact due to the introduction of new infrastructures. These models must provide a reliable knowledge about the sources and causes of pollution, about the technological and behavioural parameters and about the potentials of different control strategies. Moreover, these models need to be suitably integrated with the models representing the traffic behaviour in order to constitute a solid model basis to be used in control schemes. Among the several environmental impacts of road traffic, this chapter is mainly devoted to consider air pollution and to analyse some existing and innovative models for traffic emissions. It can be noted that also models for evaluating fuel consumption could be found in the literature, but they will be not analysed in detail in this book, being less interesting for traffic control purposes.

The vehicle emission models are conceived in order to evaluate the impact of traffic flows on air quality. Indeed, these models require as inputs the traffic data from adequate traffic flow models or from real measurements (e.g. traffic flow, traffic composition, vehicle speed and vehicle acceleration). Such models generally estimate the air pollution produced in a specific traffic scenario, providing the emission level for each type of pollutant, related to a reference time or space unit. The outputs produced by emission (or consumption) models may be distinguished in two categories, as done in [1]. The two categories are the following:

- *local emission factors*, which describe the produced emissions (or the consumed fuel) per space unit;
- *instantaneous emission factors*, which describe the produced emissions (or the consumed fuel) per time unit.

In general, both local and instantaneous emission factors depend on several aspects, such as the ones listed in the following:

- *mechanical characteristics of vehicles*: the presence of pollutant elements in the exhaust gases is mainly due to anomalies during the combustion process, whereas the introduction of CO_2 and heat is an inevitable consequence of this phase. Other factors that determine the production of pollutants depend on the air–fuel ratio, the ignition timing, the compression ratio of the engine and the geometric characteristics of the cylinders. Finally, the presence of devices that enable the reduction of pollutant emissions must be considered, i.e. the adoption of filters and traps, exhaust gas recirculation, advanced systems of valves control and many others;
- *fuel characteristics*: the type and quantity of emitted pollutants largely depend on the type of fuel used (such as gasoline, diesel, liquefied petroleum gas, etc.) and by its quality;
- *vehicle operating conditions*: driving style and operating conditions have a significant influence on the emission rates and fuel consumption (see for instance the study reported in [2]). In particular, the greatest contribution depends on the engine temperature and on the driving phases, i.e. acceleration, deceleration and cruise mode. Specifically, it is experimentally analysed that, during the acceleration phases, the quantity of polluting substances emitted is greater than the one produced during the other phases of motion. Another relevant aspect is represented by road morphology: the presence of slopes or intersections may negatively affect the level of produced emissions.

The emission factors obtained from traffic emission models may be used either for offline evaluations, or for applications in real-time monitoring tools. With reference to the first purpose, in case no effective emission measurements are available, emission models are applicable to generate emission inventories. An example of these approaches is illustrated in [3], where different models have been adopted and compared in order to propose a new inventory approach based on mean speed distributions.

Additional offline procedures require the adoption of emission models in order to quantify the environmental impact caused by the modification of the transport offer. In this regard, in [4] the benefits of traffic light coordination on the reduction of pollutant emissions are evaluated, in [5] the effect of roundabout operations on the environment is illustrated, whereas in [6] a study to assess the air quality near traffic intersections is conducted. An interesting similarity with the Braess Paradox is shown in [7]. Indeed, in this latter work, in analogy with [8, 9], it is found that the improvement of the network capacity can lead to an increase in the emissions generated by traffic.

Moreover, the emission models may be adopted to verify the effectiveness of traffic control measures in the abatement of the environmental damage. This was done, for instance in [10], which illustrates the advantages, in terms of emission reduction, produced through the implementation of traffic control systems during the 2008 Olympic Games in Beijing, or in [11–13], where the effect of variable speed limits on the level of traffic emissions is discussed. With reference to real-time applications, the methods that include the use of emission models within control schemes are discussed in detail in Chap. 10: some examples are the works [14–17] in the freeway context and [18] in the urban context.

Finally, besides the evaluation of emission factors, the concentrations of harmful substances in the environment may be quantified through dispersion emission models. These models, on the basis of the emission source, the morphological and meteorological characteristics of the site, produce an indication on the concentration of pollutants in the environmental system. In the literature, many models of pollutant dispersion have been proposed, some of these are reported in [19–21]. In this chapter, only traffic emission models and their adoption in traffic flow models are analysed, whereas dispersion models are not treated, since all the aspects related to the dispersion of pollutants are out of the scope of the book.

6.2 Classification

The existing traffic emission models aimed at estimating pollutant emission levels can be classified according to the complexity of the necessary input information and the aggregation level of the variables that describe them. Indeed, in the different models used for evaluating emissions, the model variables and their relations may describe this phenomenon at different levels of detail. Analogously to traffic flow models, emission models can be classified in

- *macroscopic models*, based on aggregate variables that allow to compute, in a simplified way, the overall pollutant emissions on road portions;
- *microscopic models*, where emission factors are associated with single vehicles and are computed starting from an accurate description of the physical processes underlying the phenomenon;
- *mesoscopic models*, that represent an intermediate description level between microscopic and macroscopic models.

In the following, an outline of the main models that belong to each of these categories and that can be useful for freeway traffic control is reported. Then, two models are described in detail, i.e. the COPERT model (Sect. 6.3) and the VERSIT+ model (Sect. 6.4), which have already been applied in traffic control schemes, as deeply discussed in Chap. 10.

6.2.1 Macroscopic Emission Models

Macroscopic emission models provide an approximate representation of the real emission processes, adopting aggregate parameters and variables. Different from microscopic models, they are not based on a faithful representation of the physical phenomena that generate the emission rates, but they take into account aggregate and average information. Thanks to this feature, macroscopic models allow to analyse the entire transport system without requiring the high computational effort needed by microscopic representations, and this surely represents a relevant advantage of such models. In light of these considerations, macroscopic emission models are the most suitable for being adopted in freeway traffic control schemes, also because these latter are normally based on traffic models which are macroscopic as well.

Besides the so-called *area-wide models* that are mainly used for planning purposes (and are, thus, outside the scope of this book), macroscopic models are further classified in average-speed emission models, traffic-situation emission models and traffic-variable emission models.

Average-speed emission models allow to make a rather realistic estimation with the lowest computational effort and, therefore, they are quite suitable to be embedded in on-line traffic control schemes. These models provide the average values of the emission factors of each harmful substance, for different categories of vehicles, as a function of the average speed in a certain road link. The output produced by these models is a local emission factor, namely the mass of pollutant emitted per space unit and per vehicle. Generally, these models are formulated so that the average speeds implicitly consider the various phases of motion, thereby increasing the accuracy of the model. An example is the COPERT model proposed in [22–24] and discussed in detail in Sect. 6.3. Another model of this category is MOBILE [25], which is, instead, insensitive to changes in the driving cycle and requires very detailed information about the type of vehicles, the used fuel and the environmental conditions. Other average-speed emission models are the Elemental model [26, 27], developed in urban contexts, which expresses the consumption of fuel through a linear function of the average trip time for a unit distance, and the Watson model [28], where the variation of speed during the trip is partially taken into account.

Another class of macroscopic models is represented by *traffic-situation emission models*, which express the relations between emission factors (and fuel consumption) and specific traffic conditions. More specifically, instead of the average-speed trajectory, this kind of models receives in input several sets of driving patterns. Each driving pattern reproduces the behaviour of different driving conditions (e.g. free-flow, congested, stop-and-go) and traffic scenarios (freeway, rural road, arterial road, urban road). Examples of traffic-situation emission models are, for instance, the HBEFA model [29], where the traffic emissions are related to different types of vehicles, to traffic situations and to the adopted fuel, and the ARTEMIS model, proposed in [30], in which the effect of different driving conditions is considered through a set of sub-models.

The third class of macroscopic models is represented by *traffic-variable emission models*. The emission factors generated by these models are dependent on the average dynamic traffic variables (speed, density, flow and queue length) and on the characteristics of the transport infrastructures. In some cases, suitable correction factors are introduced to consider the variance of the traffic variables. An example of such models is reported in [31].

6.2.2 Microscopic Emission Models

Within the wide range of models for estimating traffic emissions, microscopic models surely provide the most accurate evaluation of vehicular pollutants. Indeed, compared with macroscopic models, these models are based on a more precise knowledge of the dynamics of individual vehicles (e.g. instantaneous speed and acceleration), on the road geometry and on environmental features (such as temperature and air humidity). Microscopic emission models are especially used in the assessments of local pollution conditions, relying on their disaggregation level and the high number of required input data. Examples of such applications are shown in [4, 5, 18].

In the literature, several microscopic emission models exist, which may be classified in speed-profile emission models and modal emission models. Readers interested in a more comprehensive description are referred to [1]. In this section, only the main features of these models are addressed by referring to the most recent literature.

Speed-profile emission models use as input data the speed trajectories of a single vehicle with high temporal resolution. These trajectories are not directly used by the model, but grouped into some speed-profile factors identified for specific driving cycles. These speed-profile factors, suitably completed with additional information (such as classes of vehicles, environmental factors, road information), allow to generate the instantaneous or local emission factors for several pollutants. Among these types of models, it is worth recalling the MEASURE model [32, 33].

Differently from speed-profile emission models, which evaluate the substances emitted from vehicular traffic through some aggregation factors of the single vehicle speed profile, the *modal emission models* directly adopt the instantaneous information obtained from microscopic flow models or from traffic detectors. Modal emission models may also be distinguished in three categories:

- *emission map models*: they are presented in the form of matrices in which, for each kind of emission types and vehicle categories, one dimension represents the range of the possible speeds while the other indicates the possible areas of specific power or acceleration. Hence, the instantaneous emissions are assigned to each cell of the matrix representing a combination of the vehicle speed and acceleration (or power) observed at a specific time instant. Several limitations characterise these models, since these maps may be sparse and sensitive to the driving cycle used to generate them, as well as they may be not flexible to changes in the boundary conditions.

Further information about properties and possible applications of emission maps are discussed in [34];

- *regression-based models*: they generally make use of instantaneous speed and acceleration relations obtained from linear regressions. These models, on the one hand, allow to overcome the inaccuracies of emission map models, but, on the other hand, the absence of an accurate physical relation can lead to unrealistic results. In the literature, several approaches concerning statistical models are described. Some examples can be found in the modelling framework proposed in [35], the POLY model [36], the CMEM model [37], the VT-micro model [38, 39] and the VERSIT+ model [40]. This latter model will be described in detail in Sect. 6.4;
- *load-based models*: they rely on a careful analysis of the physical and chemical processes that give rise to pollutant emissions, where the main variable is represented by the rate of fuel consumption. Although these models are very effective in the description of emission and consumption phenomena, they require a high number of input parameters that makes them more suitable for punctual applications than for the analysis of traffic flows. An example of load-based models can be found in [41], whereas a detailed description of this model is reported in [42].

6.2.3 Mesoscopic Emission Models

Mesoscopic emission models represent an intermediate description level between microscopic and macroscopic models. In fact, in analogy with traffic flow models, mesoscopic emission models have a higher aggregation level of variables than the microscopic ones, while they are more detailed compared with the macroscopic models. In contrast with macroscopic models, that are based on average variables (i.e. the average speed), mesoscopic models can carry out a more accurate estimation without reaching the high level of detail of microscopic models.

One example is the approach proposed in [43], where fuel consumption is computed by decomposing the driving cycle in its primary components, i.e. idling acceleration, cruise and deceleration phases. This model is similar to the one used in the TRANSYT-7F simulation tool [44]. Another type of mesoscopic model is the mesoscopic version of the VT-model presented in [45], where the consumption rates of fuel are estimated as functions of the average speed, the number of stops and the average length of each stop.

6.3 The COPERT Model for Freeway Traffic Systems

In the definition of freeway traffic control schemes, a suitable choice is the adoption of aggregate models computing emissions as dependent on the main traffic variables. Actually, in this way, the control scheme can include both the traffic flow model describing the system dynamic evolution and the model for the computation of the emissions. Consequently, the control scheme can take into account explicitly, not only the reduction of traffic congestion phenomena, but also the emissions produced by vehicles in the freeway system.

Average-speed emission models have been used in some control approaches (see for instance [15, 46, 47]) to compute the impact of freeway traffic control on air quality. One of the major advantages in adopting average-speed emission models for control purposes is that they require a low computational effort.

A straightforward and widely known average-speed emission model is represented by the so-called COPERT model. COPERT has been introduced by the European Environment Agency in order to realise national and regional emission inventories for the CORINAIR project. The CORINAIR project was developed for the first time in 1985 [48] and successively updated in 1990 [49]. The aim of this project was to produce an extensive inventory of anthropogenic emissions (not only those generated by the road sector), by dividing them into different categories. The COPERT model was initially proposed in [50] and then implemented in the tool COPERT II [22]. Subsequent modifications to the model were made in COPERT III [23], in COPERT 4 [24] and in COPERT 5, which represents the most recent version of the model.

The most updated versions of the model cover a wide variety of pollutant types, in particular the following ones are examined:

- chemical compounds as carbon monoxide (CO), hydrocarbons (HC) (both methane (CH_4) and non-methane volatile organic compounds (NMVOC)), nitrogen oxides NO_x, sulphur oxides (SO_x) and particulate matter (PM);
- greenhouse gases such as nitrous oxide (N_2O), methane (CH_4), sulphur (SF_6) and carbon dioxide (CO_2);
- toxic substances as dioxins, furans, heavy metals, and carcinogenic species as persistent organic pollutants (POPs) and polycyclic aromatic hydrocarbons (PAHs).

However, if for substances such as CO, NO_x, NMVOC and PM, the model produces a rather accurate estimation, for the emissions of CO_2, SO_x, N_2O, CH_4, the evaluations produced by the model are derived from estimates of fuel consumptions and are, thus, less precise. Furthermore, in order to meet the technological advances required by the European Union for the reduction of emissions of harmful substances, COPERT computes the emission factors of a considerable range of vehicles, distinguishing them on the basis of the emission control technologies installed on board of vehicles.

In the COPERT model, the total emissions are computed as the sum of three components, i.e. hot emissions produced during the stabilised engine operation, cold emissions produced during the warming-up phase following the cold starts of the vehicle, and evaporative emissions associated with the evaporative phenomenon. In order to evaluate the impact of freeway traffic, in this chapter and in the remaining chapters of the book only *hot emissions* will be considered. The interested reader may refer to [24, 51] for the calculation of the other types of emissions.

In the following, the COPERT model is firstly introduced for different types of vehicles (Sect. 6.3.1) and, then, in Sect. 6.3.2 its adoption in a multi-class traffic flow model is discussed.

6.3.1 The COPERT Model

In the COPERT model, the emission factors concerning hot emissions are exclusively dependent on the average speed of vehicles, through rather simple relations. COPERT covers a broad range of vehicles, only some of which are illustrated in this section, with specific attention to the relations used in traffic control problems and recalled in Chap. 10.

An important distinction is between passenger vehicles and heavy-duty vehicles, that can be associated with cars and trucks, respectively, in case a two-class traffic flow model is adopted (see Sect. 6.3.2).

Let us start from *passenger cars* and let us consider J different legislation emission categories; for instance, in [24], $J = 4$ categories are considered, from Euro 1 to Euro 4, whereas, in [51], they have been extended to $J = 6$ categories, adding EURO 5 and EURO 6. By relying for instance on the COPERT model proposed in [24], for a gasoline passenger car of legislation emission category j, $j = 1, \ldots, 4$, the local emission factor for each single vehicle, related to the hot emissions of a given type of pollutant, is function of the mean speed v_j^{car}, with v_j^{car} between 10 and 130 [km/h]. Specifically, the emission factor of a single car $\Xi_j^{\text{car}}(v_j^{\text{car}})$ [g/km] is obtained as

$$\Xi_j^{\text{car}}(v_j^{\text{car}}) = \frac{a_j^{\text{car}} + e_j^{\text{car}} v_j^{\text{car}} + f_j^{\text{car}} (v_j^{\text{car}})^2}{1 + b_j^{\text{car}} v_j^{\text{car}} + d_j^{\text{car}} (v_j^{\text{car}})^2} \tag{6.1}$$

where a_j^{car}, b_j^{car}, d_j^{car}, e_j^{car} and f_j^{car}, $j = 1, \ldots, 4$, are parameters assuming specific values according to the considered type of pollutant [24].

Figure 6.2 shows the curves of CO emissions depending on the traffic mean speed for cars for the four legislation emission categories, according to (6.1) and with the values of the parameters defined in [24]. It is worth highlighting that such profiles strongly change according to the legislation emission category; Euro 1 and Euro 2 cars present the lowest emission factors for intermediate values of the average speed, whereas Euro 3 and Euro 4 cars show increasing curves, i.e. the lowest emission factors correspond to the lowest speeds.

Analogously, for *trucks, buses and coaches*, the emission factor computed by COPERT depends on the average speed of vehicles, again divided in classes, from Euro 1 to Euro 6. Several relations may be used to calculate the emission factor of a generic vehicle of type h, with h indicating a specific class of heavy vehicles, with given loading conditions and specific characteristics of the slope of the road, and referring to a specific legislation emission category j, $j = 1, \ldots, J$ [24, 51].

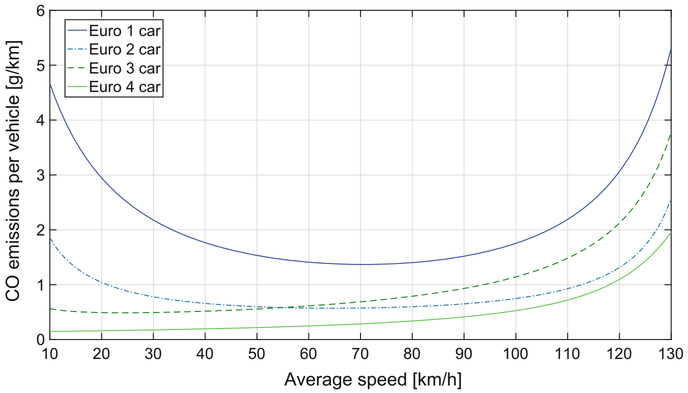

Fig. 6.2 CO emissions for passenger cars in COPERT model

Specifically, the emission factor of a single vehicle $\Xi_j^h(v_j^h)$ [g/km] depends on its main speed v_j^h. The most common relations are

$$\Xi_j^h(v_j^h) = a_j^h + b_j^h v_j^h + \frac{(c_j^h - b_j^h)(1 - \exp(-d_j^h v_j^h))}{d_j^h} \tag{6.2}$$

$$\Xi_j^h(v_j^h) = e_j^h + a_j^h \exp(-b_j^h v_j^h) + c_j^h \exp(-d_j^h v_j^h) \tag{6.3}$$

$$\Xi_j^h(v_j^h) = \frac{1}{c_j^h (v_j^h)^2 + b_j^h v_j^h + a_j^h} \tag{6.4}$$

$$\Xi_j^h(v_j^h) = \frac{1}{a_j^h + b_j^h (v_j^h)^{c_j^h}} \tag{6.5}$$

$$\Xi_j^h(v_j^h) = \frac{1}{a_j^h + b_j^h v_j^h} \tag{6.6}$$

$$\Xi_j^h(v_j^h) = a_j^h - b_j^h \exp\left(-c_j^h (v_j^h)^{d_j^h}\right) \tag{6.7}$$

$$\Xi_j^h(v_j^h) = a_j^h + \frac{b_j^h}{1 + \exp\left(-c_j^h + d_j^h \ln(v_j^h) + e_j^h v_j^h\right)} \tag{6.8}$$

$$\Xi_j^h(v_j^h) = c_j^h + a_j^h \exp(-b_j^h v_j^h) \tag{6.9}$$

$$\Xi_j^h(v_j^h) = c_j^h + a_j^h \exp(b_j^h v_j^h) \tag{6.10}$$

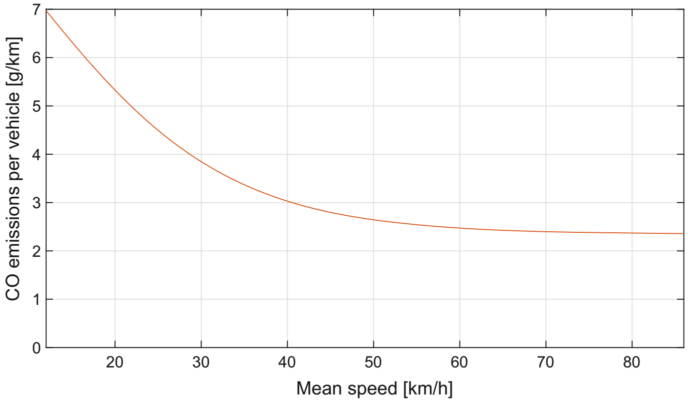

Fig. 6.3 CO emissions for Euro 1 trucks in COPERT model

$$\varXi_j^h(v_j^h) = \exp\left(a_j^h + \frac{b_j^h}{v_j^h}\right) + c_j^h \ln(v_j^h) \tag{6.11}$$

where $a_j^h, b_j^h, c_j^h, d_j^h, d_j^h$ are the model parameters, $j = 1, \dots, J$.

Let us consider now a specific case, i.e. half-loaded trucks of Euro 1 class (i.e. $j = 1$) for roads with no slope. The COPERT model [24] computes the emission factor of a single vehicle of this type, denoted ad $\varXi_1^{\text{truck}}(v_1^{\text{truck}})$ [g/km], as function of the mean speed v_1^{truck}, with v_1^{truck} between 12 and 86 [km/h], as

$$\varXi_1^{\text{truck}}(v_1^{\text{truck}}) = a_1^{\text{truck}} + \frac{b_1^{\text{truck}}}{1 + \exp\left(-c_1^{\text{truck}} + d_1^{\text{truck}} \ln(v^{\text{truck}}) + e_1^{\text{truck}} v_1^{\text{truck}}\right)} \tag{6.12}$$

which is derived from (6.8).

Figure 6.3 shows the profile of CO emissions for half-loaded trucks of Euro 1 class in case of roads with no slope, as functions of the mean speed of the vehicle, according to (6.12), with the values of the parameters defined in [24]. It is worth noting that the curve of the emission factor shows a decreasing profile with the average speed, i.e. the highest emissions are produced with low speeds (this behaviour is the opposite compared to the one of the Euro 3 and Euro 4 cars shown in Fig. 6.2).

6.3.2 Use of COPERT in a Traffic Flow Model

The COPERT model can be used associated with a traffic flow model in order to compute the emissions in a given freeway stretch or in a given freeway network. Generally speaking, if an emission model is adopted, it is useful to consider a multi-class traffic flow model instead of a single-class traffic model representing the entire flow as composed of only one typology of vehicles. This is because different types of vehicles are characterised by different emission factors and, to compute the emissions in an accurate way, it is useful to distinguish the traffic flow in different classes, at least by distinguishing cars and trucks. Moreover, the use of a second-order model seems more appropriate than a first-order model, since in the former the mean speed is explicitly modelled with its own dynamics.

Referring in particular to the second-order METANET model of multi-class type, the case of a freeway stretch and the case of a freeway network should be distinguished, as discussed in Sect. 4.3. Let us consider the multi-class second-order model for a freeway stretch described in Sect. 4.3.1, in the specific case of two classes of vehicles, i.e. cars (indicated with $c = 1$) and trucks (denoted with $c = 2$). Considering a given freeway stretch with N road sections (L_i being the length of section $i = 1, \dots, N$) and a time horizon of K time steps, it is first of all possible to compute the number of vehicles of class c present in the mainstream, in a given section $i = 1, \dots, N$ and at a given time step $k = 0, \dots, K$. This number of vehicles is denoted as $n_i^{M,c}(k)$ and depends on the density $\rho_i^c(k)$, i.e.

$$n_i^{M,c}(k) = L_i \rho_i^c(k) \tag{6.13}$$

Then, it is straightforward to compute the mainstream emissions $E_i^M(k)$ [g/km] in a given section i and at a given time step k, by summing the emission factors of each single vehicle over the number of vehicles present in the road section at that time step, i.e.

$$E_i^M(k) = n_i^{M,1}(k) \sum_{j=1}^{J} \gamma_j^1 \Xi_j^1 \left(v_j^1(k)\right) + n_i^{M,2}(k) \Xi_1^2 \left(v_1^2(k)\right) \tag{6.14}$$

where $\Xi_j^1(v_j^1(k))$ and $\Xi_1^2(v_1^2(k))$ are computed, respectively, as in (6.1) and (6.12), while γ_j^1, $j = 1, \dots, J$ represent the composition rates of cars of legislation emission j. Obviously, these composition rates must be such that $\sum_{j=1}^{J} \gamma_j^1 = 1$. Note that, by adopting (6.12) in (6.14), it is assumed that all the trucks are of the same type, but it is quite easy to extend (6.14) to consider multiple types of trucks, with emission factors defined according to (6.2)–(6.11).

Analogously, it is possible to compute the on-ramp emissions starting from the number of vehicles in the on-ramp $n_i^{R,c}(k)$ given by

$$n_i^{R,c}(k) = l_i^c(k) \tag{6.15}$$

The on-ramp emissions $E_i^R(k)$ [g/km] in section i at time step k are obtained by summing the emission factors over the number of vehicles involved, i.e.

$$E_i^R(k) = n_i^{R,1}(k) \sum_{j=1}^{J} \gamma_j^1 \alpha_j^1 + n_i^{R,2}(k) \alpha_1^2 \tag{6.16}$$

where α_j^1, $j = 1, \ldots, J$, are constant emission factors obtained from (6.1) in case of minimum average speed equal to 10 km/h. Analogously, α_1^2 is obtained from (6.12) with the speed equal to 12 km/h.

Note that the application of COPERT to a multi-class second-order model for a freeway network (as the one described in Sect. 4.3.2) is very similar to the case of the freeway stretch, with a slightly different notation.

6.4 The VERSIT+ Model for Freeway Traffic Systems

Average-speed models, such as the COPERT model, are surely efficient from a computational point of view, since they are based on speed measurements (or estimations) only. It is, however, evident that a detailed evaluation of pollutant emissions should also depend on accelerations.

VERSIT+ is a statistical emission model that belongs to the class of regression-based models and computes the emission factor of each single vehicle on the basis of its speed and acceleration. It allows to compute many types of pollutant emissions, such as HC, CO, NO_x, PM_{10} and CO_2, for a wide range of vehicles and for several traffic conditions. The study was proposed for the first time in [52], significantly reflecting the Dutch fleet composition, and was based on over 20.000 measurements (performed both on cold and hot engines) and on more than 3.200 vehicles, for a period longer than 20 years. The chosen population size and the duration of the experimentation allowed to obtain a significant sample in terms of traffic scenarios, vehicle technologies, levels of maintenance and types of fuels. In the original version of the model, the computation of the emission factor was exclusively dependent on the average speed. An improved version of the VERSIT+ model was proposed in [40] in order to achieve a more accurate estimation.

The adoption of VERSIT+ in a traffic model allows to obtain an accurate estimate of the emissions, without a too high computational load, thanks to the limited number of parameters and the rather simple formulation of the model. This is the reason why the use of VERSIT+ in a traffic model is suitable for implementation in online control schemes.

In order to adopt VERSIT+ in a macroscopic traffic flow model, it is necessary to estimate the average acceleration of vehicles starting from the average speed provided by the model. In Sect. 6.4.1 the VERSIT+ model is described, while its use in a traffic model is discussed in Sect. 6.4.2, where a procedure to compute the average accelerations of vehicles is reported.

6.4.1 The VERSIT+ Model

As aforementioned, the VERSIT+ model [40] includes, in the computation, not only the average speed, but also the average acceleration. In particular, the emission factor of a generic vehicle of type h produced by the model depends on two terms. The former is a combination of the acceleration a^h [m/s^2] and the speed v^h [km/h], included in the model through the dynamic variable w^h defined as

$$w^h = a^h + 0.014 v^h \tag{6.17}$$

The latter term is the speed value v^h [km/h], which is divided in four categories corresponding to different driving conditions: idling conditions when $v^h < 5$ and $a^h < 0.5$, urban driving with $v^h \leq 50$, rural driving with $50 < v^h \leq 80$ and freeway driving with $v^h > 80$.

Specifically, the emission factor Ξ^h for each vehicle of type h [kg/s] is given by

$$\Xi^h = \begin{cases} u^{h,0} & \text{if } v^h < 5 \text{ and } a^h < 0.5 \\ u^{h,1} + u^{h,2} w^h_+ + u^{h,3} (w^h - 1)_+ & \text{if } v^h \leq 50 \\ u^{h,4} + u^{h,5} w^h_+ + u^{h,6} (w^h - 1)_+ & \text{if } 50 < v^h \leq 80 \\ u^{h,7} + u^{h,8} (w^h - 0.5)_+ + u^{h,9} (w^h - 1.5)_+ & \text{if } v^h > 80 \end{cases} \tag{6.18}$$

where $u^{h,j}$, with $j = 0, \ldots, 9$, are coefficients of the emission model, whereas the function $(x)_+$ imposes the non-negativity of the variable x, i.e. $(x)_+ = 0$ if $x < 0$ and $(x)_+ = x$ otherwise.

6.4.2 Use of VERSIT+ in a Traffic Flow Model

Analogously to COPERT (see Sect. 6.3.2), also the VERSIT+ model can be associated with a traffic flow model to compute the emissions in a freeway stretch or network. In particular, a multi-class traffic model is surely more suitable than a single-class model, since it is able to distinguish different classes of vehicles that can present quite different emission factors. If the adoption of COPERT in a traffic flow model is rather straightforward, the application of VERSIT+ requires the computation of accelerations, that are not directly provided by the traffic model.

The extension of VERSIT+ to be used in a macroscopic traffic model was introduced in [14, 53], where two types of acceleration have been identified, i.e. the segmental acceleration considering the speed variation within a road section, and the cross-segmental acceleration, which concerns the speed variation of vehicles moving from one road section to the next one, between two consecutive time steps. In [54, 55], such accelerations were extended to the multi-class case, while in [56] the model was extended to add the computation of the emissions at the on-ramps.

Let us refer to the second-order METANET model of multi-class type representing a freeway stretch, described in Sect. 4.3.1, in which the time horizon is partitioned into time intervals with sample time T, with K the number of time steps, and the freeway stretch is divided into N road sections, with L_i being the length of road section $i = 1, \dots, N$. In order to apply VERSIT+, it is first of all necessary to provide a methodology for evaluating the average accelerations of vehicles for each road section, for each class of vehicles and for every simulation time step. This methodology is different for vehicles travelling in the mainstream and for vehicles moving, instead, at the on-ramps. These two aspects are separately described in the following.

Mainstream Emissions In order to evaluate the emissions due to vehicles travelling in the mainstream, the average acceleration and the number of vehicles involved have to be computed for each road section $i = 1, \dots, N$, for each class of vehicles $c = 1, \dots, C$, and for every time step $k = 0, \dots, K$.

Specifically, two types of acceleration are considered in the freeway links, i.e.

- the *segmental acceleration* $a_i^{\text{seg,c}}(k)$ represents the speed variation of vehicles of class c within section i between time step k and time step $k+1$; the number of vehicles subject to this acceleration is denoted as $n_i^{\text{seg,c}}(k)$;
- the *cross-segmental acceleration* $a_{i,i+1}^{\text{cross,c}}(k)$ is the speed variation of vehicles of class c moving from section i to section $i+1$ between time step k and $k+1$; the number of vehicles involved is indicated with $n_{i,i+1}^{\text{cross,c}}(k)$.

The two types of acceleration are computed on the basis of the mean speed $v_i^c(k)$, respectively, as follows:

$$a_i^{\text{seg,c}}(k) = \frac{v_i^c(k+1) - v_i^c(k)}{T} \tag{6.19}$$

$$a_{i,i+1}^{\text{cross,c}}(k) = \frac{v_{i+1}^c(k+1) - v_i^c(k)}{T} \tag{6.20}$$

Moreover, the number of vehicles subject to segmental and cross-segmental accelerations is obtained depending on the traffic density $\rho_i^c(k)$ and the traffic flow $q_i^c(k)$, i.e.

$$n_i^{\text{seg,c}}(k) = L_i \rho_i^c(k) - T q_i^c(k) \tag{6.21}$$

$$n_{i,i+1}^{\text{cross,c}}(k) = T q_i^c(k) \tag{6.22}$$

By taking into account the computation of the average accelerations and the number of vehicles involved, it is possible to evaluate the mainstream emissions associated with each road section and each time step. More specifically, by taking into account (6.18), the emission factor due to the segmental acceleration, referred to section i and time step k, can be computed as follows:

$$\Xi_i^{\text{seg,c}}(k) = \begin{cases} u^{c,0} & \text{if } v_i^c(k) < 5 \text{ and } \\ & \quad a_i^{\text{seg,c}}(k) < 0.5 \\ u^{c,1} + u^{c,2} w_i^{\text{seg,c}}(k)_+ + u^{c,3}(w_i^{\text{seg,c}}(k) - 1)_+ & \text{if } v_i^c(k) \leq 50 \\ u^{c,4} + u^{c,5} w_i^{\text{seg,c}}(k)_+ + u^{c,6}(w_i^{\text{seg,c}}(k) - 1)_+ & \text{if } 50 < v_i^c(k) \leq 80 \\ u^{c,7} + u^{c,8}(w_i^{\text{seg,c}}(k) - 0.5)_+ + u^{c,9}(w_i^{\text{seg,c}}(k) - 1.5)_+ & \text{if } v_i^c(k) > 80 \end{cases} \tag{6.23}$$

where the dynamic variable $w_i^{\text{seg,c}}(k)$ is computed according to (6.17), i.e.

$$w_i^{\text{seg,c}}(k) = a_i^{\text{seg,c}}(k) + 0.014 v_i^c(k) \tag{6.24}$$

Analogously, the emission factor due to the cross-segmental acceleration, referred to section i and time step k, is given by

$$\Xi_{i,i+1}^{\text{cross,c}}(k) = \begin{cases} u^{c,0} & \text{if } v_i^c(k) < 5 \text{ and } \\ & \quad a_{i,i+1}^{\text{cross,c}}(k) < 0.5 \\ u^{c,1} + u^{c,2} w_{i,i+1}^{\text{cross,c}}(k)_+ + u^{c,3}(w_{i,i+1}^{\text{cross,c}}(k) - 1)_+ & \text{if } v_i^c(k) \leq 50 \\ u^{c,4} + u^{c,5} w_{i,i+1}^{\text{cross,c}}(k)_+ + u^{c,6}(w_{i,i+1}^{\text{cross,c}}(k) - 1)_+ & \text{if } 50 < v_i^c(k) \leq 80 \\ u^{c,7} + u^{c,8}(w_{i,i+1}^{\text{cross,c}}(k) - 0.5)_+ + u^{c,9}(w_{i,i+1}^{\text{cross,c}}(k) - 1.5)_+ & \text{if } v_i^c(k) > 80 \end{cases} \tag{6.25}$$

where $w_{i,i+1}^{\text{cross,c}}(k)$ is computed as

$$w_{i,i+1}^{\text{cross,c}}(k) = a_{i,i+1}^{\text{cross,c}}(k) + 0.014 v_i^c(k) \tag{6.26}$$

According to (6.23) and (6.25), it is possible to compute the mainstream emissions $E_i^M(k)$ [kg/s] in a given section i and a given time step k, summing the emission factors of each single vehicle over the number of vehicles present in the section at that time step, i.e.

$$E_i^M(k) = \sum_{c=1}^{C} \left[n_i^{\text{seg,c}}(k) \Xi_i^{\text{seg,c}}(k) + n_{i,i+1}^{\text{cross,c}}(k) \Xi_{i,i+1}^{\text{cross,c}}(k) \right] \tag{6.27}$$

On-ramp Emissions When dealing with freeways, it is important to evaluate the emissions of vehicles not only in the mainstream, but also at the on-ramps, in order to correctly take into account the emission phenomena along the overall system. In fact, the operating conditions of vehicles queuing at the on-ramps are quite important and the associated emissions should be included in the total calculation of traffic emissions.

Referring to a generic on-ramp of road section i, four groups of vehicles are introduced and four types of acceleration are considered:

- the acceleration $a_i^{\mathrm{a,c}}(k)$ of *arriving vehicles*, i.e. vehicles of class c arriving at the on-ramp of section i at time step k and waiting in the queue at $k+1$; the number of arriving vehicles is denoted as $n_i^{\mathrm{a,c}}(k)$;
- the acceleration $a_i^{\mathrm{w,c}}(k)$ of *waiting vehicles*, i.e. vehicles of class c moving within the queue of the on-ramp of section i between time step k and $k+1$; let $n_i^{\mathrm{w,c}}(k)$ indicate the number of waiting vehicles;
- the acceleration $a_i^{\mathrm{ls,c}}(k)$ of *leaving vehicles with stop*, i.e. vehicles of class c being in the queue of the on-ramp of section i at time step k and exiting the on-ramp at $k+1$; let $n_i^{\mathrm{ls,c}}(k)$ indicate the number of leaving vehicles with stop;
- the acceleration $a_i^{\mathrm{lns,c}}(k)$ of *leaving vehicles without stop*, i.e. vehicles of class c arriving at the on-ramp of section i at time step k and exiting the on-ramp at $k+1$ without any intermediate stop in the queue; let $n_i^{\mathrm{lns,c}}(k)$ indicate the number of leaving vehicles without stop.

Analogously to the mainstream emissions, it is necessary to compute the mean accelerations and the number of vehicles involved, for each of these four groups of vehicles.

The acceleration of arriving vehicles is given by

$$a_i^{\mathrm{a,c}}(k) = \frac{v_i^{\mathrm{idl,c}}(k+1) - v_i^{\mathrm{on,c}}(k)}{T} \tag{6.28}$$

where $v_i^{\mathrm{on,c}}(k)$ is the speed of vehicles arriving at the on-ramp and $v_i^{\mathrm{idl,c}}(k)$ is the speed of vehicles moving within the queue of the on-ramp.

The acceleration of waiting vehicles is computed as

$$a_i^{\mathrm{w,c}}(k) = \frac{v_i^{\mathrm{idl,c}}(k+1) - v_i^{\mathrm{idl,c}}(k)}{T} \tag{6.29}$$

The acceleration of leaving vehicles with stop is obtained as

$$a_i^{\mathrm{ls,c}}(k) = \frac{v_i^{c}(k+1) - v_i^{\mathrm{idl,c}}(k)}{T} \tag{6.30}$$

while the acceleration of leaving vehicles without stop is given by

$$a_i^{\mathrm{lns,c}}(k) = \frac{v_i^{c}(k+1) - v_i^{\mathrm{on,c}}(k)}{T} \tag{6.31}$$

The number of vehicles that belong to each group is computed depending on the value of the flow $r_i^c(k)$ leaving the on-ramp and entering the mainstream. In particular, two cases may be distinguished:

1. if $0 \leq r_i^c(k) \leq \frac{l_i^c(k)}{T}$, corresponding to the case in which the vehicles entering the mainstream are fewer than the vehicles in the queue (see Fig. 6.4), the number of vehicles of the four groups is given by

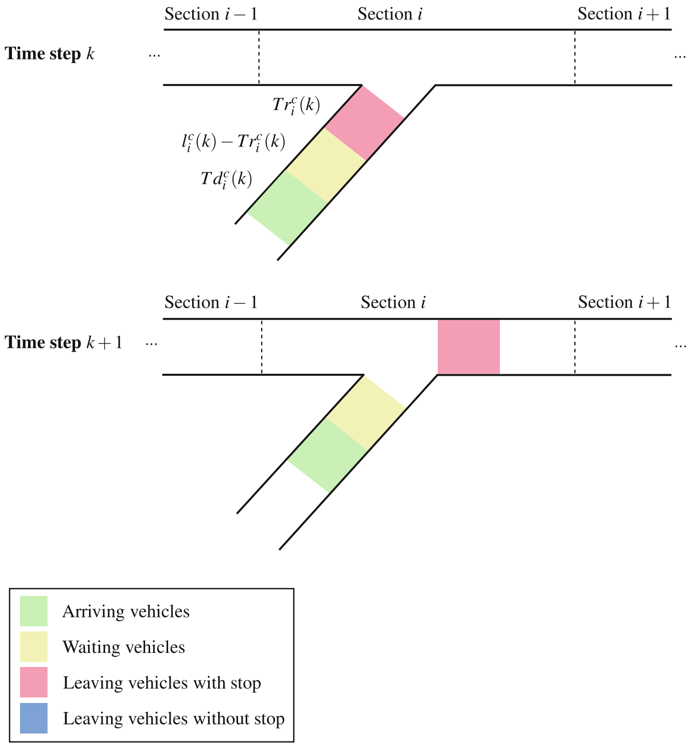

Fig. 6.4 Groups of on-ramp vehicles if $0 \le r_i^c(k) \le \frac{l_i^c(k)}{T}$

$$n_i^{\mathrm{a,c}}(k) = Td_i^c(k) \tag{6.32}$$

$$n_i^{\mathrm{w,c}}(k) = l_i^c(k) - Tr_i^c(k) \tag{6.33}$$

$$n_i^{\mathrm{ls,c}}(k) = Tr_i^c(k) \tag{6.34}$$

$$n_i^{\mathrm{lns,c}}(k) = 0 \tag{6.35}$$

2. if $\frac{l_i^c(k)}{T} < r_i^c(k) \le d_i^c(k) + \frac{l_i^c}{T}(k)$, corresponding to the case in which the vehicles entering the mainstream are more than the vehicles in the queue (see Fig. 6.5), the number of vehicles is obtained as

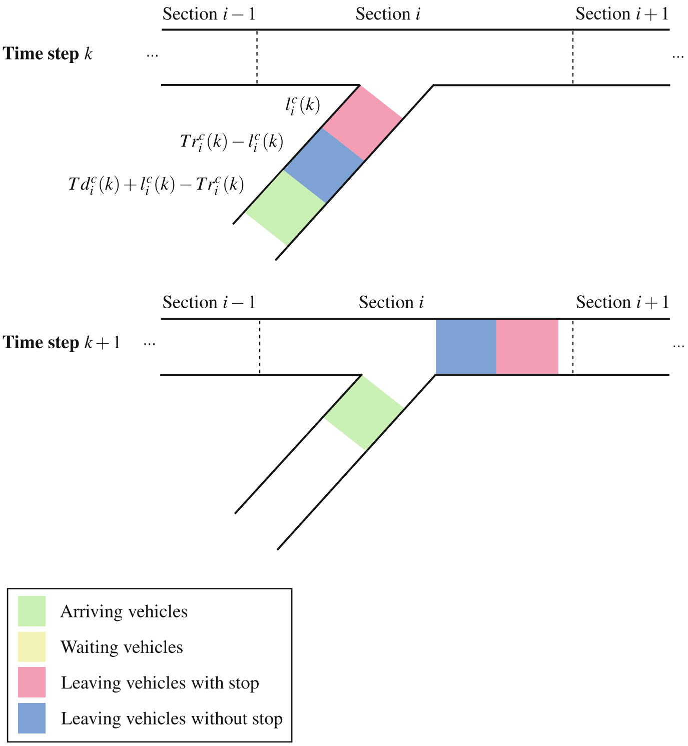

Fig. 6.5 Groups of on-ramp vehicles if $\frac{l_i^c(k)}{T} < r_i^c(k) \leq d_i^c(k) + \frac{l_i^c}{T}(k)$

$$n_i^{\mathrm{a,c}}(k) = Td_i^c(k) + l_i^c(k) - Tr_i^c(k) \tag{6.36}$$

$$n_i^{\mathrm{w,c}}(k) = 0 \tag{6.37}$$

$$n_i^{\mathrm{ls,c}}(k) = l_i^c(k) \tag{6.38}$$

$$n_i^{\mathrm{lns,c}}(k) = Tr_i^c(k) - l_i^c(k) \tag{6.39}$$

The emission factors for the four groups of vehicles at the on-ramps can be computed analogously to the mainstream case. For notational purposes, let us define the speed values related to the four groups of vehicles $y \in Y = \{\mathrm{a}, \mathrm{w}, \mathrm{lns}, \mathrm{ls}\}$, in the on-ramp of section i at time step k, as follows:

$$v_i^{y,c}(k) = \begin{cases} v_i^{\text{on,c}}(k) & \text{if } y = \text{a, lns} \\ v_i^{\text{idl,c}}(k) & \text{if } y = \text{w, ls} \end{cases} \tag{6.40}$$

The emission factors related to the generic on-ramp group $y \in Y$ in the on-ramp of section i at time step k are computed as

$$\Xi_i^{y,c}(k) = \begin{cases} u^{c,0} & \text{if } v_i^{y,c}(k) < 5 \text{ and} \\ & \quad a_i^{y,c}(k) < 0.5 \\ u^{c,1} + u^{c,2} w_i^{y,c}(k)_+ + u^{c,3}(w_i^{y,c}(k) - 1)_+ & \text{if } v_i^{y,c}(k) \le 50 \\ u^{c,4} + u^{c,5} w_i^{y,c}(k)_+ + u^{c,6}(w_i^{y,c}(k) - 1)_+ & \text{if } 50 < v_i^{y,c}(k) \le 80 \\ u^{c,7} + u^{c,8}(w_i^{y,c}(k) - 0.5)_+ + u^{c,9}(w_i^{y,c}(k) - 1.5)_+ & \text{if } v_i^{y,c}(k) > 80 \end{cases} \tag{6.41}$$

where the dynamic variable $w_i^{y,c}(k)$ is calculated as

$$w_i^{y,c}(k) = a_i^{y,c}(k) + 0.014 v_i^{y,c}(k) \tag{6.42}$$

By taking into account (6.41), the on-ramp emissions $E_i^R(k)$ [kg/s] in section i at time step k are obtained by summing the emission factors over the number of vehicles, i.e.

$$E_i^R(k) = \sum_{c=1}^{C} \sum_{y \in Y} n_i^{y,c}(k) \Xi_i^{y,c}(k) \tag{6.43}$$

Note that the application of VERSIT+ to the multi-class second-order model for a freeway network (described in Sect. 4.3.2) is rather similar to the one of a freeway link, but a slightly different notation should be adopted, specifically at the boundary between two adjacent links, i.e. when vehicles move between the last section of a link and the first section of the downstream link. Further details can be found in [16, 57].

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